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ENVIRONMENTAL TOBACCO SMOKE IN COMMERCIAL AIRCRAFT

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Abstract—Environmental tobacco smoke and other pollutants present in both smoking and nonsmoking cabin sections during commercial passenger flights on DC-10 aircraft were determined on four, 5-h smoking flights. The average concentrations of nicotine, 3-ethenylpyridine, CO_2, CO, NO_y, NO_2, O_3, PM2.5 and environmental tobacco smoke particles during a flight were determined with a briefcase sampling system. Concentrations of nicotine, 3-ethenylpyridine and CO as well as temperature, humidity and pressure were determined as a function of time during the flight. A model to predict penetration of environmental tobacco smoke from the smoking to the nonsmoking section of the passenger cabin under a variety of flight conditions is derived from the data.

Key word index: Environmental tobacco smoke (ETS), aircraft, nicotine, 3-ethenylpyridine, UV-PM, CO, air quality, dispersion model, NO_2, Briefcase Automated Sampling System (BASS), PM2.5.

INTRODUCTION

Determination of the concentrations of environmental tobacco smoke (ETS) in various indoor environments has been emphasized during recent years because of the suspected health hazards and irritant effects associated with exposure to ETS. Various indoor environments where ETS may be present, e.g. homes (Eatough *et al.*, 1989a; Henderson *et al.*, 1987), restaurants (Eudy *et al.*, 1987; Hammond and Coghlin, 1987) and work environments (Eatough *et al.*, 1989a; Hammond and Coghlin, 1987, Hammond *et al.*, 1988; Vaughn and Hammond, 1989) have been studied. There has been an increased interest in determining exposure to ETS in commercial aircraft by quantifying the concentrations of pollutants associated with ETS, determining the factors which control the concentrations of ETS present in nonsmoking sections of passenger cabins and developing models for predicting exposure.

Smoking on commercial aircraft has been a debated issue. A National Academy of Sciences report (NAS, 1986) recommended banning smoking on all commercial flights for the following reasons: minimization of irritation, reduction of health risks and fire hazards, and to bring levels of pollutants in cabin air in line with those in other indoor environments. In April 1988, the U.S. Congress enacted a temporary law banning smoking on all flights of 2 h or less. In February 1990, a new law went into effect which banned smoking on domestic U.S. airline flights shorter than 6 h. Similar legislation is in effect in Canada.

Several studies have determined the concentrations of ETS components present in commercial aircraft cabins. Concentrations of nicotine present in the cabin environment in a number of commercial aircraft flights (Oldaker and Conrad, 1987; Nagda *et al.*, 1990; Mattson *et al.*, 1989; Muramatsu *et al.*, 1987) have been reported. The exposure of airline flight attendants (Mattson *et al.*, 1989; Foliart *et al.*, 1983) and passengers (Eatough *et al.*, 1990a; Mattson *et al.*, 1989) to environmental tobacco smoke has been estimated from measurements of nicotine and cotinine in urine. Oldaker *et al.* (1990) have reported the concentrations of nicotine, RSP and UV-PM on several long, commercial flights using a portable air sampling system. Similar sampling systems were used to determine the concentrations of nicotine, CO and RSP at four locations in the passenger cabin of flights on MD-80 aircraft (Malmfors *et al.*, 1989) and on a variety of U.S. flights (Nagda *et al.*, 1990). The latter three studies are the only studies reported to date which have attempted to correlate the concentrations of nicotine in the passenger cabin of commercial aircraft with the concentrations of other constituents of environmental tobacco smoke. Löfroth *et al.* (1988) have measured the mutagenicity of particles collected during air travel in nonsmoking sections. Concentrations of RSP or NO_2 have also been determined in a limited number of experiments in cabin environments with segregated smoking and nonsmoking sections (NAS, 1986).

Most of the studies have used nicotine as the tracer to quantify exposure. However, exposure calculations based only on nicotine will underestimate total exposure to ETS since nicotine is removed from indoor

environments at rates faster than other species associated with ETS (Eatough *et al.*, 1990b; Tang *et al.*, 1989).

We have measured a variety of compounds associated with ETS as well as several non-unique species (such as PM2.5 and CO) in both smoking and nonsmoking sections of aircraft cabins. The spectrum of species and aircraft sampled is intended to provide a database for the development of models for the prediction of ETS concentrations in aircraft cabins under a variety of conditions. This paper presents the results obtained from a series of DC-10 flights.

METHODS

Sampling equipment and analysis methods

Data were collected by four volunteers using Briefcase Automated Sampling Systems (BASS) (Eatough *et al.*, 1989b). The inlet to the BASS was a Teflon tube located at about breathing height and fastened to the seat in front of the volunteer. The tube led to the BASS located under the seat in front of the volunteer. The inlet tube was connected to a Teflon cyclone (University Research Glassware) with a 2.5 μm particle size cut for coarse particle removal. Following the cyclone was a Teflon-coated manifold from which the various systems in the BASS sampled the cabin air. Each BASS used two dual Spectrex Model A-400 vacuum pumps powered by rechargeable Ni-Cd batteries. Real-time data collection and sample system control was done by a microprocessor. Flow through the various systems was controlled by an adjustable critical orifice after each system. A complete description of the sampling systems used in the BASS has been given (Eatough *et al.*, 1989b). A brief description of each system used to determine the concentrations of the species reported in this paper follows.

System 1. A 3-micron Teflon membrane filter (Teflo, Gelman Sciences) was used to collect particles for the gravimetric determination of particle concentrations. Air was drawn through the system at a nominal rate of 8 sLpm.

System 2. Two mini-annular denuder sections (Koutrakis *et al.*, 1989) coated with benzenesulfonic acid (BSA) for collection of gas-phase nicotine and 3-ethenylpyridine (Caka *et al.*, 1990) were followed by a 1-micron Teflon filter (Zefluor, Gelman Sciences) for collection and determination of nicotine (Eatough *et al.*, 1989c) and UV-PM (Carson and Erikson, 1988; Oldaker *et al.*, 1990). Following the Teflor filter was a BSA saturated filter for the collection of any nicotine lost from particles during sampling (Caka *et al.*, 1990; Eatough *et al.*, 1989c). Air was drawn through the system at a rate of 2 sLpm.

All sampling components in system 2, with the exception of the Teflon filter, were extracted with water and the extracts analysed by ion chromatography for nicotine and 3-ethenylpyridine (Lewis *et al.*, 1990). The Teflon filter was extracted with methanol, with half of the extract analysed for UV absorbance using a spectrophotometer to determine UV-PM (Carson, 1988), and the other half analysed for nicotine by ion chromatography (Lewis *et al.*, 1990).

System 3. The air distribution manifold of the BASS contained ports for sampling through Tenax microtube samplers (Eatough *et al.*, 1990b; Caka *et al.*, 1990). Each microtube was sequentially switched into the sampling line during a flight. The selection of each tube for sampling was controlled using solenoid values. Air flow was controlled at 0.1 sLpm using a variable micro-orifice. The nicotine and 3-ethenylpyridine collected by selected microtubes were determined using capillary column chromatography as previously described (Tang *et al.*, 1988).

System 4. A series of sorbent tubes (Dräger) were used to determine the average concentrations of CO_2, CO, NO_x, NO_2 and O_3 during a flight. Air was drawn through each tube at 0.2 sLpm except for the O_3 Dräger tubes which were sampled at 0.5 sLpm. Concentrations were read directly from each tube following each flight. The readings were converted to a flight-integrated concentration using the sample flow rate and sampling time. The CO_2, CO and NO_x Dräger tubes were calibrated in chamber experiments using freshly generated environmental tobacco smoke by comparing the results obtained with those obtained using gas monitors (Eatough *et al.*, 1990c).

System 5. A total of five instruments were used to make real-time measurements in the BASS. Real-time monitors for temperature, pressure and humidity (Omega Model HX91 and 14LPC18A) were located near the air exit ports in the side of the BASS for two of the instruments. The concentrations of CO and CO_2 were determined continuously in two BASS instruments during some of the flights using CO electrochemical sensors (Neutronics, OTOX Sensor) and a micro CO_2 combination electrode (Microelectrodes Inc., Model MI-270). Both chemical sensors measured the concentrations of the target gas in a flowing air stream from the central manifold at a flow rate of about 0.03 sLpm. The CO sensors were housed in an H_2O permeation chamber designed to introduce H_2O vapor to the membrane to avoid drying out of the sensor membrane. The concentrations of CO determined in chamber experiments using the real-time sensor, a CO Dräger tube and the IR instrument on the 30 m^3 Teflon chamber were in agreement (Eatough *et al.*, 1989b).

Sampling protocol

Four volunteer nonsmokers participated in four DC-10 flights. Each volunteer carried one BASS and was seated in the rear passenger cabin which contained the economy class smoking section at the rear of the aircraft. The location of the subjects in each flight is given in Table 1. All flights were about 5 h in length. Flights 1 and 3 and flights 2 and 4 were the same origination and destination, however, a different aircraft was flown for each flight. Prior to each flight, the BASS batteries were charged to ensure maximum power throughout the flight, and flow calibrations were done on each system using calibrated rotometers. Once aboard the aircraft, sampling was begun after take off when the no-smoking sign was turned off. Sampling was concluded when the no-smoking sign was turned on prior to landing. Smoking activity was observed and recorded by the person in the smoking section. At the conclusion of the flight, all cigarette butts at each seat in the smoking section ashtrays were counted. At the conclusion of each flight, flow calibrations were once again done on each system in the BASS. Samples were recovered and stored at 0 °C until analysed.

RESULTS AND DISCUSSION

The flight-averaged concentrations of the various species measured for samples collected in the smoking and nonsmoking sections during the four DC-10 flights are given in Table 2. Changes in the temperature, humidity, pressure and frequency of smoking during a typical flight are shown in Fig. 1. Changes in the concentration of 3-ethenylpyridine measured over 25-min intervals during a flight with heavy smoking in the smoking section and four rows in front of the smoking section as a function of the frequency of smoking during the time of sample collection are shown in Fig. 2. The frequency of smoking for the data

Table 1. Location of the various persons responsible for collection of samples on each flight

Flight no.	Smoking section	No. of cigarettes smoked during flight	Subject	Seat
1	rows 34–37	115	I	35 D
			II	17 D
			III	34 G
			IV	32 J
2	rows 34–37	32	I	33 A
			II	24 C
			III	33 C
			IV	34 C
3	rows 32–37	218	I	30 D
			II	31 F
			III	26 F
			IV	32 F
4	rows 34–37	76	I	35 D
			II	29 C
			III	33 D
			IV	24 F

Table 2. Concentrations of environmental tobacco smoke constituents in the smoking section of DC-10 cabins during a 4–5-h flight. The subjects for each flight are in order of increasing distance from the smoking section

Flight, subject	UV-PM ($\mu g\,m^{-3}$)	PM2.5 ($\mu g\,m^{-3}$)	Gaseous nicotine ($nmol\,m^{-3}$)	Particle nicotine ($nmol\,m^{-3}$)	3-Ethenyl pyridine ($nmol\,m^{-3}$)	CO (ppm)	NO_x (ppb)	NO_2 (ppb)
1.I	NA*	202	345.6	0.0	33.1	0.79	30	4
1.III	NA	203	224.1	0.0	10.0	0.14	22	2
1.IV	NA	32	15.4	0.0	1.1	0.26	7	1
1.II	NA	16	0.1	0.0	0.0	0.19	7	0
2.IV	NA	75	84.3	0.0	4.3	0.30	7	2
2.III	NA	29	39.2	0.0	2.1	0.19	7	0
2.I	NA	85	78.4	0.0	4.3	0.20	7	2
2.II	NA	33	0.1	0.0	0.0	NA	NA	NA
3.IV	360	NA†	471.6	3.1	20.2	1.94	36	0
3.II	251	213	305.5	−1.2	13.9	1.29	25	1
3.I	144	118	123.8	3.4	8.0	0.54	22	0
3.III	34	56	20.4	5.4	2.5	0.16	8	1
4.I	113	140	128.6	−1.2	5.6	0.96	25	2
4.III	48	83	35.8	−1.1	1.6	1.05	8	0
4.II	14	45	6.5	5.7	1.0	0.68	0	0
4.IV	8	40	1.2	0.0	0.3	0.79	10	0

* NA = not analysed.
† Assumed equal to UV-PM plus background PM2.5 in the data analyses.

in Fig. 2 is given as the equivalent number of cigarettes per seat in the smoking section over the entire flight to allow direct comparison with the flight-averaged concentrations. The variation of the background corrected (Table 3), flight-averaged concentrations of the species measured with seat location is illustrated in Fig. 3. The background concentrations of PM2.5, CO and NO_x were either determined from measurements made remote from the smoking section or from linearization of plots such as that shown in Fig. 3. Complete data for the four flights are available (Eatough *et al.*, 1990c).

Ventilation in a DC-10 (NAS, 1986) is controlled by three air cycle machines which introduce fresh air equally along the length of the cabin. The air is then exhausted at the same longitudinal distance that it was introduced with no air recirculation. Ventilation was operated at maximum and was about the same (reported to be 30 air changes per hour) for each of the four flights. The flight-averaged concentration of environmental tobacco smoke constituents in the smoking section of each flight should then be controlled by the number of cigarettes smoked and the size of the smoking section.

The observed flight-integrated concentrations of environmental tobacco smoke species in the smoking section were directly dependent on the number of cigarettes smoked per seat in the smoking section (Fig. 4). The regression lines in Fig. 4 include the origin, consistent with the hypothesis that non-

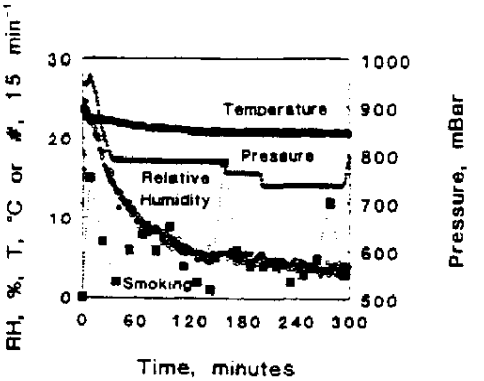

Fig. 1. Variation with time of the temperature, pressure, humidity and number of cigarettes smoked in a 15-min interval during flight 3.

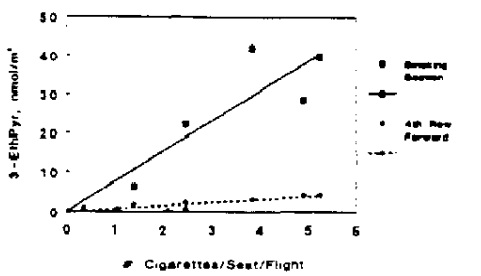

Fig. 2. Variation in the concentration of 3-ethenylpyridine at a smoking section and nonsmoking section seat with the frequency of cigarette smoking in the smoking section for 25-min sample collection during flight 1. The frequency of smoking has been given as an equivalent entire flight frequency to allow direct comparison with the flight integrated data.

ETS sources of the various constituents have been accounted for. The concentration of nicotine for the flight with 2.7 cigarettes smoked per seat is a statistical outlier and is not included in the calculation of the regression lines given in Fig. 4. The concentrations in the smoking section per cigarette per seat during the flights averaged (arithmetic mean values throughout

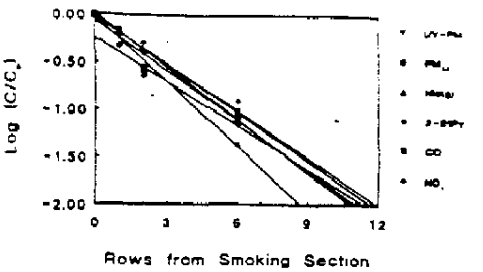

Fig. 3. Log(C/C_0), where C_0 is the concentration in the smoking section, both C and C_0 corrected for the background concentration, vs number of rows from the smoking section into the nonsmoking section for flight 3.

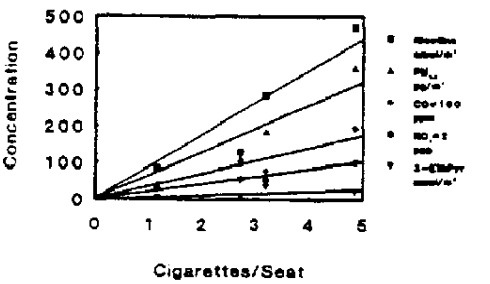

Fig. 4. Concentration of nicotine, UV-PM, CO and 3-ethenylpyridine in the smoking section of DC-10 aircraft during 5-h flights as a function of the number of cigarettes smoked per seat in the smoking section during the flight.

the text) 64 ± 7 μg PM2.5 m^{-3}, 86 ± 10 nmol nicotine m^{-3}, (14 ± 2 μg nicotine m^{-3}) 5.3 ± 1.7 nmol 3-ethenylpyridine m^{-3}, 0.35 ± 0.04 ppm CO and 6.3 ± 0.2 ppb NO_x. From the slopes of the regression lines in Fig. 4, ratios of UV-PM mass, nicotine, 3-ethenylpyridine and NO_x to CO present in the environmental tobacco smoke in the smoking sections are calculated to be 4.4 ± 0.5 g UV-PM per mol CO, 27 ± 3 mmol NO_x per mol CO, 6.5 ± 0.5 mmol nicotine per mol CO and 0.37 ± 0.05 mmol 3-ethenylpyridine per mol CO. These ratios are comparable to the expected ratio of 4.2 ± 0.8 g UV-PM per mol CO and 39 ± 4 mmol NO_x

Table 3. Background concentrations in DC-10 cabins during 4–5-h flights with smoking permitted

Flight	UV-PM (μg m⁻³)	PM2.5 (μg m⁻³)	Nicotine (nmol m⁻³)	3-Ethenyl pyridine (nmol m⁻³)	CO (ppm)	NO_x (ppb)	CO_2 (%)	O_3 (ppb)
1	NA*	16	<1	<1	0.2	7	0.17	<2
2	NA	32	<1	<1	0.1	7	0.11	15
3	<3	29	<1	<1	0.0	6	0.13	<2
4	<3	35	<1	<1	0.6	6	0.21	20
Average	<3	28	<1	<1	0.2	7	0.15	9

* NA = not analysed.

per mol CO, but smaller than the expected ratios of 12.8 ± 4.0 mmol nicotine per mol CO and 1.4 ± 0.5 mmol 3-ethenylpyridine per mol CO, based on the composition of fresh sidestream tobacco smoke (Eatough *et al.*, 1990b). However, the ratio of 3-ethenylpyridine to CO in the aircraft cabins is comparable to that found in indoor environments where smoking is present, 0.34 ± 0.10 mmol 3-ethenylpyridine per mol CO (Eatough *et al.*, 1989a) and in an experimental chamber with environmental tobacco smoke generated by smokers, 0.89 ± 0.10 mmol 3-ethenylpyridine per mmol CO (Caka *et al.*, 1991). The ratio of nicotine to CO in the aircraft cabins is higher than that found in these same indoor environments, 0.9 ± 0.4 mmol nicotine per mol CO (Eatough *et al.*, 1989a) or in a chamber with smokers, 3.0 ± 1.0 mmol nicotine per mol CO (Caka *et al.*, 1990; Löfroth *et al.*, 1989).

The expected absolute concentrations of these species may be estimated from the known number of cigarettes smoked, expected sidestream emission per cigarette smoked (Eatough *et al.*, 1990b), volume of the smoking section and air exchange rate in the cabin. For example, for flight 3, the flight with the highest smoking frequency and the observed highest concentrations of environmental tobacco smoke constituents, the expected flight-integrated concentrations of nicotine, UV-PM and CO in the smoking section are calculated to be 840 ± 200 nmol nicotine per m^{-3}, 300 ± 75 μg m^{-3} and 1.6 ± 0.4 ppm CO, respectively. These predicted concentrations can be compared to the measured concentrations of 472 nmol nicotine m^{-3}, 360 μg UV-PM m^{-3} and 2.2 ppm CO, respectively. The measured concentrations of UV-PM and CO are in reasonable agreement with the calculated concentrations. However, the measured concentration of nicotine is about half the predicted concentration. All of these data are consistent with the rapid removal of nicotine in an indoor environment (Eatough *et al.*, 1990b; Tang *et al.*, 1989). For example, in studies in the chamber at the U.S. Environmental Protection Agency (Löfroth, 1989) the ratio of PM2.5 to nicotine in environmental tobacco smoke in the empty chamber was 3.0 g PM2.5 per g nicotine, a ratio consistent with the value obtained for sidestream smoke (Eatough *et al.*, 1990b; Guerin *et al.*, 1987) and in inert chambers (Eatough *et al.*, 1989c; Benner *et al.*, 1989; Thompson *et al.*, 1989). When the chamber had people in it with a small air exchange rate, the measured ratio was 13 g PM2.5 per g nicotine. The ratio measured in the smoking section of the aircraft cabin with a high air exchange rate, 4.9 ± 0.8 g PM2.5 per g nicotine, is between these two values.

The concentrations of NO_2 in the cabin environments were always a small fraction of the total NO_x, e.g. results given in Table 2. The ozone data suggest that there are reactive compounds present in the environmental tobacco smoke in the passenger cabins. The concentration of ozone tends to decrease as the concentration of environmental tobacco smoke constituents increases with location in the cabin as illustrated by the data in Fig. 5. This same effect was seen in all the flights (Eatough *et al.*, 1990c).

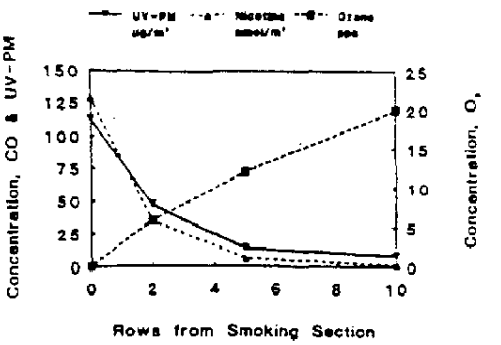

Fig. 5. Variation in the concentrations of UV-PM, nicotine and ozone as a function of seat location for flight 4.

Penetration of environmental tobacco smoke constituents from the smoking into the nonsmoking section of the aircraft will be controlled by the rate of diffusion of gas-phase compounds between the two sections and by the rate of mixing of air along the length of the aircraft perpendicular to the exhaust gradient. The rate of penetration of gas-phase compounds into the nonsmoking section will only be greater than the rate of penetration of particulate phase species if diffusion is a more important process than mixing. Both of these processes should be described by first-order exponentials and a plot of the log of the concentration of a species vs distance from the smoking section should be linear. If there are other sources of any of the measured environmental tobacco smoke constituents other than in the smoking section, the plot will show a positive deviation from the expected linearity with distance, e.g. a less positive slope. Background corrected first-order penetration plots for the various species measured in flight 3 are shown in Fig. 3. Similar results were obtained for the other flights as shown for all species except nicotine in Fig. 6.

The data in Figs 3 and 6 follow the expected linear decrease in the log of the concentration (normalized to the concentration measured in the smoking section, C_o). Results on the rate of change of $\log(C/C_o)$ with distance into the smoking section for all species for all four flights are given in Table 4. The results given in Table 4 are calculated using background corrected concentrations (Table 3). Correction of the data in the nonsmoking section for background concentrations was only important for PM2.5, CO and NO_x; compare the data in Tables 2 and 3. The calculated rate of penetration of ETS components into the nonsmoking section, Table 4, falls into three groups:

1. The nicotine concentration decreases most rapidly with distance. Nicotine in the cabin environment (Table 2) is predominantly in the gas phase. The

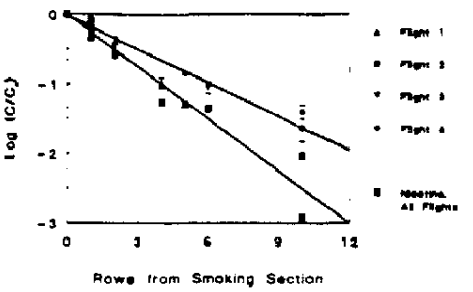

Fig. 6. Log(C/C_o), where C_o is the concentration in the smoking section, both C and C_o corrected for the background concentration, vs number of rows from the nonsmoking section into the smoking section for all species but nicotine and for nicotine for all flights. The regression lines are given for nicotine only and for all other species.

rapid decrease in gas-phase nicotine with distance from the smoking section parallels the concentration of nicotine in the smoking section being less than expected compared to other constituents of environmental tobacco smoke and can be attributed to the more rapid removal of gas-phase nicotine by surfaces in the cabin (Tang *et al.*, 1989).

2. The compounds with intermediate rates of concentration decrease with distance from the smoking section are UV-PM, 3-ethenylpyridine and, for flight 3 with high concentrations of environmental tobacco smoke, CO.
3. The data for PM2.5 and NO_x in all flights and for CO in flight 4 with the lowest concentrations of environmental tobacco smoke give more positive slopes than the compounds listed in (2), unless the data are corrected for background concentrations. If the PM2.5, NO_x and CO concentrations are corrected for background concentrations, the rate of penetrations of these species into the nonsmoking section is comparable to that seen for UV-PM and 3-ethenylpyridine. The data from all the flights give an average background, non-ETS concentration of 27 ± 8 μg PM2.5 m^{-3}, 0.2 ± 0.2 ppm CO, 7 ± 1 ppb NO_x and 9 ± 9 ppb O_3 in the cabin environment, see Table 3. We postulate that the background source of CO, NO_x and O_3 is from the ambient air. The data indicate that the flight with the highest concentrations of non-ETS CO was flight 4. This was also the flight with the highest concentrations of ozone in the nonsmoking sections of the aircraft, see Fig. 5.

The slopes of the various log (C/C_o) vs distance from the smoking section plots, Table 4, are a measure of the degree of penetration of environmental tobacco smoke constituents from the smoking into the nonsmoking section. These slopes were the same for all flights (Table 4 and Fig. 6). In addition, for all flights where data were available, the rate of penetration of PM2.5 (background corrected), UV-PM, 3-ethenylpyridine, CO (background corrected) and/or NO_x (background corrected) were generally the same, indicating that mixing is a more important variable than gas diffusion in determining the rate of penetration of environmental tobacco smoke from the smoking into the nonsmoking section.

The rate of decrease in the concentration of nicotine with distance into the smoking section was greater than the rate of decrease of the concentration of PM2.5, UV-PM, 3-ethenylpyridine, CO and/or NO_x for all flights except flight 2, the flight with the lowest concentration of environmental smoke. The large uncertainty in the slope calculated from the nicotine data for flight 2 results from an apparent outlier. If this point is deleted, the calculated slope is -0.29 ± 0.01. Using this value for flight 2, the slope of the plot of log (C/C_o) vs distance from the smoking section is calculated to be more negative for nicotine than the average slope for the other species by a factor of 1.2 to 2.3 (see Fig. 7). The selective removal of nicotine by the surfaces in the cabin increases with decreasing total smoking in the nonsmoking section, see Fig. 7.

Limited data were obtained on the concentrations of 3-ethenylpyridine and nicotine as a function of time during a flight. The data given in Fig. 2 were obtained

Table 4. Minus the rate of change of log (C/C_o) for background corrected environmental tobacco smoke components per row

Flight	UV-PM	PM2.5	Nic (g)*	3-EtPy†	CO	NO_x	Flight average‡
1	NA§	0.25 ± 0.05	0.31 ± 0.04	0.32 ± 0.03 (0.22 ± 0.03)‖	0.23	0.1	0.22 ± 0.02
2	NA	0.16 ± 0.02	0.18 ± 0.11 (0.29 ± 0.01)¶	0.15 ± 0.11	0.19 ± 0.01	NA	0.17 ± 0.02
3	0.17 ± 0.01	0.21 ± 0.03	0.23 ± 0.01	0.18 ± 0.01	0.19 ± 0.02	0.18 ± 0.01	0.19 ± 0.01
4	0.16 ± 0.01	0.15 ± 0.02	0.26 ± 0.00	0.15 ± 0.02	0.13 ± 0.00	NA	0.15 ± 0.01

* Nic(g) is gas-phase nicotine.
† 3-EtPy is gas-phase 3-ethenylpyridine.
‡ The average values do not include the value obtained from the nicotine data for all flights (see text) nor the value obtained from the 3-ethenylpyridine data for flight 1.
§ NA = data not available.
‖ Value obtained using the semi-real time data obtained with the Tenax sampling system.
¶ Value obtained eliminating an outlier data point, see text.

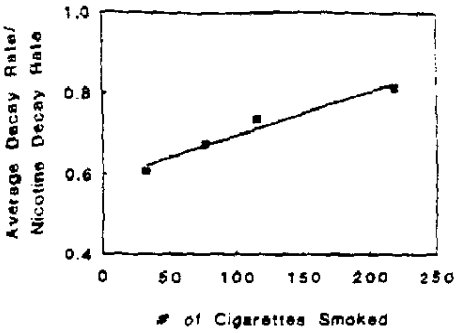

Fig. 7. Ratio of the slope of $\log(C/C_0)$, vs distance from the smoking section for nicotine as a function of the number of cigarettes smoked in the smoking section during the flight.

from 25-min samples collected sequentially on the Tenax microtubes during flight 1. The average concentration of 3-ethenylpyridine in the smoking section during the flight obtained from this data, 27 nmol m^{-3}, is in reasonable agreement with that determined using the denuder sampling system with collection at the same seat location over the entire flight, 33 nmol m^{-3}. Nicotine data are not obtained at this location. The concentrations of nicotine at a seat four rows in front of smoking determined from the semi-real time Tenax, 18 nmol m^{-3} and integrated, 15 nmol m^{-3} sampling systems, agreed. The concentrations of 3-ethenylpyridine determined using the Tenax sampling system give a value for the rate of change of $\log(C/C_0)$ of -0.22 ± 0.05 per row, in agreement with that obtained from the data for the other ETS components (Table 4). Thus, both the absolute concentration of ETS species in the smoking section as a function of the amount of smoking occurring and the rate of penetration of these species into the nonsmoking section obtained from 25-min sampling is the same as that obtained from samples collected over the various 5-h flights. The time required for concentration equilibria to be established in the passenger cabin is short compared to the flight time.

SUMMARY

The concentration of most environmental tobacco smoke constituents in the smoking section of an aircraft cabin can be calculated from the frequency of smoking during a flight, the size of the smoking section and ventilation rate. The concentration of nicotine will tend to be overestimated in this calculation due to selective loss of nicotine to cabin surfaces. The concentration of some constituents (e.g. PM2.5 and CO) may be underestimated in the calculation due to contributions of non-ETS sources to these species. CO and NO_x, as well as ozone, may be introduced to the aircraft cabin from the inlet air. The rate of penetration of environmental tobacco smoke constituents from the smoking section into the nonsmoking section follows a first-order rate law. The rate of penetration was constant for the various DC-10 aircraft flown in this study. The expected rate of decrease in the concentration of various constituents with distance into the nonsmoking section can be altered by selective removal of compounds by cabin surfaces (e.g. nicotine) or by the presence of non-ETS sources of some species in the nonsmoking section (e.g. CO, PM2.5 or NO_x). Additional data are needed to determine what variables control the first-order penetration of environmental tobacco smoke constituents from the smoking to the nonsmoking sections of a variety of aircraft. The model developed in this paper has been successfully applied to other data sets (Eatough *et al.*, 1990c; Malmfors *et al.*, 1989; Oldaker *et al.*, 1990). Manuscripts describing this extension of the concepts presented here are being prepared for publication.

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